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STOCHASTIC PROPERTIES OF PEER-TO-PEER COMMUNICATION ARCHITECTURE IN A MILITARY SETTING

by

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A time-critical military mission must be completed before a random deadline to be successful. The mission requires a number of Blue assets; the more assets that can be assembled before the deadline, the greater the possibility of mission success. Traditionally, military Command and Control (C2) has a hierarchical structure; information is centrally stored and decision makers are also centralized. The paradigm of Network-Centric Warfare (NCW) implies a more horizontal C2 structure. There is often little communication infrastructure on the battlefield. Peer-to-Peer (P2P) communication networks are attractive enablers of a horizontal C2 structure. A stochastic model is used to discuss the benefits and possible vulnerabilities of a P2P-enabled C2 structure for a time-critical mission. The P2P architecture can result in larger probabilities of mission success than centralized C2. However, its benefits are nullified if the time it takes to assemble the needed Blue assets becomes larger than that for the centralized C2.

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STOCHASTIC PROPERTIES OF PEER-TO-PEER COMMUNICATION ARCHITECTURE IN A MILITARY SETTING

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Abstract

A time-critical military mission must be completed before a random deadline to be successful. The mission requires a number of Blue assets; the more assets that can be assembled before the deadline, the greater the possibility of mission success. Traditionally, military Command and Control (C2) has a hierarchical structure: information is centrally stored and decision makers are also centralized. The paradigm of Network-Centric Warfare (NCW) implies a more horizontal C2 structure. There is often little communication infrastructure on the battlefield. Peer-to-Peer (P2P) communication networks are attractive enablers of a horizontal C2 structure. A stochastic model is used to discuss the benefits and possible vulnerabilities of a P2P-enabled C2 structure for a time-critical mission. The P2P architecture can result in larger probabilities of mission success than centralized C2. However, its benefits are nullified if the time it takes to assemble the needed Blue assets becomes larger than that for the centralized C2.

1. Problem Formulation

We consider here the situation in which a single opponent Red Agent (RA) moves surreptitiously in a designated subregion, either on earth/terrain or on or below a maritime littoral surface. Its mission may be any of a variety of options. For instance, a TEL (Transportable Erectable Launcher) is a land-based SCUD missile launcher that tries to elude detection by hiding under bridges or trees, or in caves, or even in partially empty buildings, such as barns. It becomes visible (vulnerable to attack) when it sets up to shoot at remote Blue assets, or when it is in motion across terrain (along a road) in its assigned subregion or sector. Otherwise, it is invisible (hiding or concealed). This type of target is called a *time-sensitive target.*[1] Alternatively, Blue is protecting a littoral domain, and an overhead sensor is searching for a Red (hostile and possibly lethal) platform attempting to reach, and damage, Blue assets. Overhead sensors identify the Red amongst a large background of harmless White/Friendly vessels; once identified (possibly incorrectly) reinforcement Blue surface (or air) platforms assemble to divert or destroy the suspected threat.

Another interpretation is that "the Red" is actually a friendly (Blue) downed pilot in hostile territory, and is moving about to avoid capture by opponent-Reds. Blue rescuers/recovery teams try to find and recover the pilot before hostile capture occurs.

Each subregion (one of many that comprise a larger total region) is assumed for the present to be covered by two Blue Agent (BA) types: there are n_s Blue Surveillance Agents (BSAs) and n_b Blue Attack Agents (BAAs); it is possible that the BAs are equipped both to see and to shoot, e.g. be Un-Manned Combat Aerial Vehicles (UCAVs), or armed Fixed Wing Manned Aircraft, or combinations thereof. The BSAs search the subregion "at random," and then signal, either through a central C2 authority, or directly, e.g., by "chat,"[2] to loitering BAAs when the RA is detected. Once signaled, the BAAs are given the detected RA's location and proceed thereto.

Assume the rate of arrival near to Red's location of any BAA after being signaled is Markovian with rate λ (which may depend on region or terrain), so the time a typical BAA requires finding and "attaching to" the visible RA, initiating the formation of an Engagement Pack (EP),[3] has an exponential distribution with mean $1/\lambda$ independently of the other BAAs. This formulation may be altered to reflect the particular behavior of various communication-network-forming (Peer-to-Peer=P2P) protocols.[4-7] When an EP has reached a to-be-determined size $\tilde{b}$ it (the entire EP) attacks/fires upon the RA if the RA remains visible. If the RA senses an EP, or if it finishes its assigned mission before the EP($\tilde{b}$) fully forms, it immediately hides; the BSA-BAA mission is a failure, and the Red-Hide, Blue-Seek process begins again. There are certain tradeoffs: if $n_s >> n_b$ then a visible RA may be found quickly, but relatively small EPs may be optimal because larger assemblies could alert the visible Red to hide; this lowers the lethality of B on R (but deters hostile SCUD launches). It is clear that if $\tilde{b} \le n_b$ is too small, low Blue-on-Red attack lethality may occur, while if $\tilde{b}$ is set too large the chance increases that the visible RA (potential target) senses the threat, or hastily completes its mission, and disappears. There can clearly be an optimal EP size, and the latter may realistically evolve over time as learning by both sides occurs. Also, the latter may depend on physical/environmental conditions, such as *ducting*.[8]

2. A Renewal Model for Blue vs. Red in a Subregion

Let there be n_s BSAs, and suppose each independently searches for a visible RA over the distinguished subregion, and let a typical random visible period for the RA be of independent random duration $\boldsymbol{V}$ with distribution $F_{\boldsymbol{V}}$ with $F_{\boldsymbol{V}}(0)=0$; (it is realistic that Red may alter the latter over time and experience with near-misses by Blue, but we do not address this gaming aspect of the problem at this stage). If the RA becomes visible (at t=0), then some BSA detects it at time $\boldsymbol{D}=x$ if $\boldsymbol{D}(=x)<\boldsymbol{V}$; let the Poissonian search rate of the BSA force be $\bar{\xi}=n_s\xi$; independence then implies that the probability the RA is detected before it hides is

$$p_d(BR)=\int_0^\infty \left[1-F_V(x)\right]\bar{\xi}e^{-\bar{\xi}x}dx=1-\hat{F}_{\boldsymbol{V}}\left(\bar{\xi}\right), \tag{1}$$

where

$$\hat{F}_{\boldsymbol{V}}\left(\bar{\xi}\right)=\int_{0}^{\infty} e^{-\bar{\xi} x} F_{\boldsymbol{V}}(dx) \equiv E\left[e^{-\bar{\xi} \boldsymbol{V}}\right]; \tag{2}$$

coincidentally, the Laplace-Stieltjes transform for the distribution function (d.f.) of $\boldsymbol{V}$.

Let $\boldsymbol{H}$ with d.f. $F_{\boldsymbol{H}}$ having Laplace-Stieltjes transform $\hat{H}(s)$ denote an arbitrary hiding time; and let $\{\boldsymbol{H}(n)\}$ and $\{\boldsymbol{V}(n)\}$ be mutually independent sequences of independent, identically distributed random variables. It is easily possible to allow their distributions to be conditional on, say, environmental factors (ducting, sea state, terrain, etc.) and on the actual types of RAs and BAs in play.

2.1. The Visibility Detection Process is Terminating Renewal

The temporal history of a RA can be (initially) modeled and analyzed, e.g., by probabilistic mathematics or Monte Carlo simulation, as an alternating renewal process.[9] Suppose the RA initially begins hiding. Then assume it is in hiding during the random intervals

$\left[0, \boldsymbol{H}(1)\right], \left[\boldsymbol{H}(1)+\boldsymbol{V}(1), \boldsymbol{H}(1)+\boldsymbol{V}(1)+\boldsymbol{H}(2)\right], \ldots.$

It is visible on the complementary intervals

$\left[\boldsymbol{H}(1), \boldsymbol{H}(1)+\boldsymbol{V}(1)\right],$

$\left[\boldsymbol{H}(1)+\boldsymbol{V}(1)+\boldsymbol{H}(2), \boldsymbol{H}(1)+\boldsymbol{V}(1)+\boldsymbol{H}(2)+\boldsymbol{V}(2)\right], \ldots.$

To model detection of the RA requires the BSA surveillance capability, which is represented as occurring at rate $\bar{\xi}=n_S \xi$ over the subregion.

2.2. Model

Take this convenient if simplified approach to BSA detection. If an element of BSA force arrives when the RA is hiding, no detection of the RA is possible, whereas if the hidden RA becomes visible (for time $\boldsymbol{V}$) then assume that its detection occurs if a BSA unit arrives near the RA location at time $\boldsymbol{D}$ after the RA emerges and before it hides again. The probability of this event is given by (1) above (assume that the RA does not detect the BSA and immediately hide; such capability could induce a more surreptitious BSA concept of operations (CONOPS)).

Let $\boldsymbol{T}_D$ denote the random first BSA detection time of a visible RA, given that RA has initially become visible at time 0. Then

$$\boldsymbol{T}_D=\begin{cases}\boldsymbol{D} & \text{if } \boldsymbol{D}<\boldsymbol{V}(1), \\ \boldsymbol{V}(1)+\boldsymbol{H}(1)+\boldsymbol{T}_D' & \text{if } \boldsymbol{D}>\boldsymbol{V}(1)\end{cases} \tag{3}$$

where $\boldsymbol{T}_D'$ is an independent replica of $\boldsymbol{T}_D$. It is straightforward to calculate the Laplace-Stieltjes transform $E\left[e^{-s\boldsymbol{T}_D}\right]$:

$$\psi_{\boldsymbol{T}_D}(s)=\frac{\bar{\xi}\left[1-\hat{F}\left(s+\bar{\xi}\right)\right]}{\left(s+\bar{\xi}\right)\left[1-\hat{F}\left(s+\bar{\xi}\right)\hat{H}(s)\right]}, \tag{4}$$

where $\bar{\xi}=\xi n_S$. Setting s=0 shows that $\boldsymbol{T}_D$ terminates in finite time with probability one. The Laplace transform of $P\{\boldsymbol{T}_D>t\}$ is

$$\begin{aligned}\frac{1-\psi_{\boldsymbol{T}_D}(s)}{s}&=\frac{s\left[1-\hat{F}_{\boldsymbol{V}}\left(s+\bar{\xi}\right)\hat{H}(s)\right]+\bar{\xi}\hat{F}_{\boldsymbol{V}}\left(s+\bar{\xi}\right)\left[1-\hat{H}(s)\right]}{s\left(s+\bar{\xi}\right)\left[1-\hat{F}_V\left(s+\bar{\xi}\right)\hat{H}(s)\right]}\\&=\frac{1}{s+\bar{\xi}}+\frac{\bar{\xi}}{\left(s+\bar{\xi}\right)}\frac{\hat{F}_{\boldsymbol{V}}\left(s+\bar{\xi}\right)}{\left[1-\hat{F}_{\boldsymbol{V}}\left(s+\bar{\xi}\right)\hat{H}(s)\right]}\frac{1-\hat{H}(s)}{s}.\end{aligned} \tag{5}$$

Let $s\to 0$ to see that

$$E\left[\boldsymbol{T}_D\right]=\frac{1}{\bar{\xi}}+\frac{\hat{F}_{\boldsymbol{V}}\left(\bar{\xi}\right)}{\left(1-\hat{F}_{\boldsymbol{V}}\left(\bar{\xi}\right)\right)}E\left[\boldsymbol{H}\right]. \tag{6}$$

On the set $\boldsymbol{D}<\boldsymbol{V}$ let $\boldsymbol{V}_0=\boldsymbol{V}-\boldsymbol{D}$, the remaining time the RA is visible. The Laplace transform of the remaining time the RA is visible on the set the RA is detected before it hides is

$$\begin{aligned}E\left[e^{-s\boldsymbol{V}_0};\boldsymbol{D}<\boldsymbol{V}\right]&=\int_0^\infty \bar{\xi}e^{-\bar{\xi}y}dy\int_y^\infty e^{-s(z-y)}F_{\boldsymbol{V}}(dz)\\&=\frac{\bar{\xi}}{\bar{\xi}-s}\hat{F}_{\boldsymbol{V}}(s)-\frac{\bar{\xi}}{\bar{\xi}-s}\hat{F}_{\boldsymbol{V}}\left(\bar{\xi}\right);\end{aligned} \tag{7}$$

$$\phi(s)=E\left[e^{-s\boldsymbol{V}_0}\mid \boldsymbol{D}<\boldsymbol{V}\right]=\frac{\bar{\xi}}{\bar{\xi}-s}\frac{\left[\hat{F}_{\boldsymbol{V}}(s)-\hat{F}_{\boldsymbol{V}}\left(\bar{\xi}\right)\right]}{1-\hat{F}_{\boldsymbol{V}}\left(\bar{\xi}\right)}. \tag{8}$$

This development assumes that just one detection by a BSA (the first such) is sufficient to begin to enroll an EP (capable of lethal action, or possibly pilot recovery). Otherwise, P2P communication could be used to develop a corroborative group of observers.[10-12]

2.3. The Probability an EP of Size $\tilde{b}$ Attaches to the Detected RA Before it Hides

Assume once the RA is detected, BAAs attach to it after independent exponential times each having mean $1/\lambda$ while the RA is visible. Note that more rapid EP assembly may be achieved by using a more sophisticated and situationally adapted P2P discipline. Many alternatives are possible and adaptable to changed circumstances; these are under investigation.

The conditional probability an EP of size $\tilde{b}$ forms before the RA hides given $\boldsymbol{V}_0$ is

$$P\left\{\boldsymbol{T}_{\tilde{b}} < \boldsymbol{V}_0 \mid \boldsymbol{V}_0, \boldsymbol{D} < \boldsymbol{V}\right\} = \sum_{k=\tilde{b}}^{\bar{b}} \binom{\bar{b}}{k} \left[1 - e^{-\lambda \boldsymbol{V}_0}\right]^k \left[e^{-\lambda \boldsymbol{V}_0}\right]^{\bar{b}-k}$$
$$= \sum_{k=\tilde{b}}^{\bar{b}} \binom{\bar{b}}{k} \sum_{j=0}^{k} \binom{k}{j} (-1)^j e^{-\lambda \boldsymbol{V}_0 \left[j + \bar{b} - k\right]}, \qquad (9)$$

where $\boldsymbol{T}_{\tilde{b}}$ is the time to form an EP of size $\tilde{b}$ and $\bar{b}$ is the number of BAAs in the subregion for $\tilde{b} \le \bar{b}$.

2.4. The Probability the Detected RA is Killed Before it Hides

Given $\bar{b}$, the number of BAAs in a region, we calculate the probability of Blue's successful kill of a discovered RA. Mathematically, this amounts to

$$P_K\left(\tilde{b}, \bar{b}\right) = E_{\boldsymbol{V}_0 \mid (\boldsymbol{D} < \boldsymbol{V})}\left[P\left\{\boldsymbol{T}_{\tilde{b}} \le \boldsymbol{V}_0 \mid \boldsymbol{V}_0\right\}\left(\bar{h}\right)^{\tilde{b}}\left(1 - \left(1 - p_K\right)^{\tilde{b}}\right)\right], \qquad (10)$$

where $\boldsymbol{T}_{\tilde{b}}$ is the time of first passage to $\tilde{b}$ present in an EP, $\tilde{b} \le \bar{b}$, and $\bar{h}$ is the probability that an individual BAA's arrival does not cause the RA to hide. The term $1 - \left(1 - p_K\right)^{\tilde{b}}$ denotes the probability that if all $\tilde{b}$ BAAs attached to the RA shoot, at least one hits/kills the RA; this assumes independence and simultaneous independent Blue firing success probabilities, all of which can be modified for more realism. The conditional probability the RA is killed before it hides, given the RA is detected during a visible period, is thus

$$P_K\left(\tilde{b}, \bar{b}\right)$$
$$= \left(\bar{h}\right)^{\tilde{b}}\left(1 - \left(1 - p_K\right)^{\tilde{b}}\right) \sum_{k=\tilde{b}}^{\bar{b}} \binom{\bar{b}}{k} \sum_{j=0}^{k} \binom{k}{j} (-1)^j \phi\left(\lambda\left[j + \bar{b} - k\right]\right), \qquad (11)$$

where $\phi(s)$ is defined in (8).

2.5. Model with Additional C2 Time

In addition to the time to assemble an EP there can be an additional planning/command time, ***S***, which we assume has an exponential distribution with mean $1/\alpha$, independent of the time to assemble the EP. This assumption can be justified on the basis of heavy-traffic queueing theory.[13] This is the traditional C2/I or C4ISR Central Command Time/latency; it may conservatively ensure against errors, but adds a latency penalty to Blue response. A visible RA is engaged if the time to assemble the EP, plus the planning/command time, is less than the remaining time the RA is visible. See detailed modeling of a more complex version of this problem by Brickner.[1]

$$P\left\{ \boldsymbol{S} + \boldsymbol{T}_{\tilde{b}} < \boldsymbol{V}_0 \mid \boldsymbol{V}_0, \boldsymbol{D} < \boldsymbol{V} \right\}$$
$$= \sum_{k=\tilde{b}}^{\bar{b}} \binom{\bar{b}}{k} \int_0^{\boldsymbol{V}_0} \alpha e^{-\alpha s} \left[1 - e^{-\lambda(\boldsymbol{V}_0 - s)} \right]^k \left[e^{-\lambda(\boldsymbol{V}_0 - s)} \right]^{\bar{b}-k} ds$$
$$= \sum_{k=\tilde{b}}^{\bar{b}} \binom{\bar{b}}{k} \sum_{j=0}^{k} \binom{k}{j} (-1)^j \int_0^{\boldsymbol{V}_0} \alpha e^{-\alpha s} e^{-\lambda\left[j+\bar{b}-k \right](\boldsymbol{V}_0 - s)} ds \tag{12}$$
$$= \sum_{k=\tilde{b}}^{\bar{b}} \binom{\bar{b}}{k} \sum_{j=0}^{k} \binom{k}{j} (-1)^j \frac{\alpha}{\alpha - \lambda\left(\bar{b} + j - k\right)} \left[e^{-\lambda\left(\bar{b}+j-k\right)\boldsymbol{V}_0} - e^{-\alpha \boldsymbol{V}_0} \right].$$

In this case, the conditional probability the RA is killed before it hides, given it is detected, is

$$P_K\left(\tilde{b}, \bar{b}; a\right)$$
$$= \left(\bar{h}\right)^{\tilde{b}} \left(1 - \left(1 - p_K\right)^{\tilde{b}} \right) \tag{13}$$
$$\times \sum_{k=\tilde{b}}^{\bar{b}} \binom{\bar{b}}{k} \sum_{j=0}^{k} \binom{k}{j} (-1)^j \frac{\alpha\left[\phi\left(\lambda\left[j + \bar{b} - k \right] \right) - \phi(\alpha) \right]}{\alpha - \lambda\left(\bar{b} + j - k\right)}.$$

2.6. Numerical Illustration

In this example, the time to detect a visible RA is given an exponential distribution with mean 4 minutes. The RA is visible for a random time having a gamma distribution with mean 15 minutes and shape parameter 50. The probability the target hides when a new BAA joins the EP is 0. Table 1 displays the probabilities a visible RA is killed when it is engaged by various sizes of EPs. The time for a BAA to join an EP has an exponential distribution independent of the other BAAs.

Table 1. Conditional probability an engaged visible target is killed given the size of the EP.

Size of EP	Conditional Probability of Kill
1	0.5
2	0.6
3	0.7
4	0.8
5	0.9

Figure 1 displays the probability of killing the RA during its visible period for 3 different mean additional C2 times; the mean times are 0, 3 minutes, and 5 minutes. In all cases, the mean time until a BAA joins an EP is 3 minutes. For each EP size, the number of BAAs in the region equals the needed size of the EP. The probability of killing the detected RA during its visible period is maximized for an EP of size 3 for all cases. The probability the RA will hide before a 4th BA joins an EP of size 3 nullifies the benefit of the increased probability of kill that an EP of size 4 has. Increasing the mean C2 time decreases the probability of killing the RA during its visible period for all EP sizes.

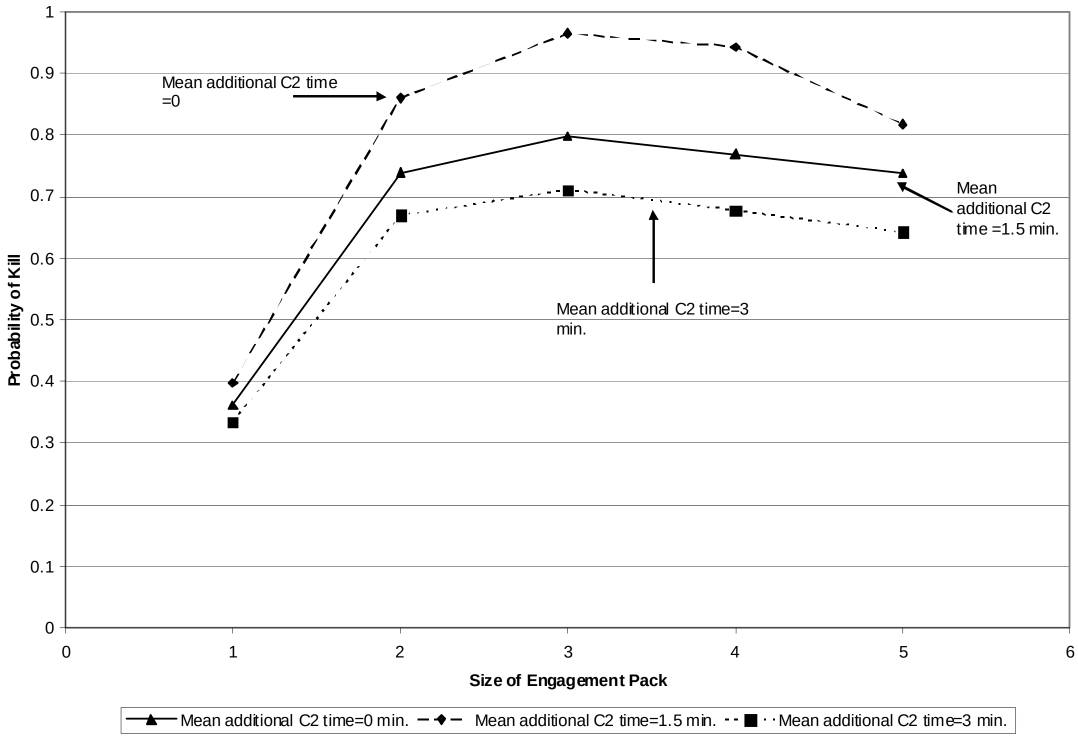

Figure 1. Probability of killing a detected RA during its remaining visible period versus the size of the EP. The length of the visible period has a gamma distribution with mean 15 minutes. and shape 50. The time to detect a visible target has an exponential distribution with mean 4 minutes. The time for a BAA to join an EP has an exponential distribution with mean 3 minutes. Note that the optimal EP size is about the same for all cases, but the actual kill probabilities are highly time-sensitive.

Figure 2 displays the probability the detected RA is killed during its remaining visible period for three cases with different mean times for a BAA to join an EP: 3 minutes, 4.5 minutes, and 6 minutes; the additional C2 time is equal to 0 for all three cases. For each EP size, the number of BAAs in the region is equal to the EP size. Note that the mean time to form an EP of size one for each case is the same as that in Figure 1. The probability of killing the detected RA during its remaining visible time is maximized for an engagement pack of size 3. Increasing the mean time for a BA to join an EP decreases the probability of kill.

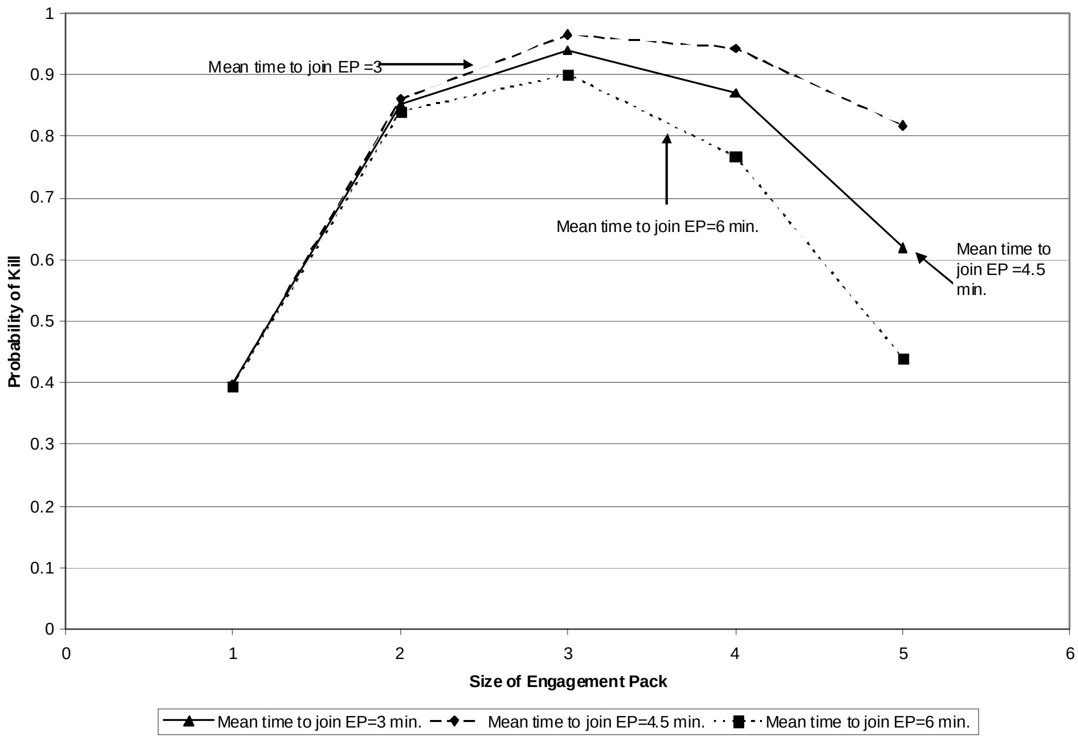

Figure 2. Probability of killing the detected RA during its remaining visible period versus the size of the EP. The length of the visible period has a gamma distribution with mean 15 minutes and shape 50. The time to detect a visible target has an exponential distribution with mean 4 minutes There is no additional C2 time.

The decrease becomes larger the larger the size of the EP. Comparison with Figure 1 reveals that for an engagement of size 5, increasing the mean time for a BAA to join an EP results is smaller probability of kill than increasing the mean additional C2 time for the cases considered.

3. Conclusions

A stochastic model for the effect of a P2P-enabled C2 architecture on the effectiveness of time-critical targeting has been presented. The numerical example suggests that P2P *can* result in increased targeting effectiveness over a centralized C2 architecture. However, if P2P results in an increased time to assemble an engagement pack to engage the target over that using a centralized C2 architecture, or if there are too many errors or too much jamming or interference, then its benefits can be nullified. The model is optimistic in that it assumes that all BAAs are available to join an EP when a target is detected and Red is not attempting to disrupt the P2P communication. The model can be modified to represent the consequences of different P2P communication networks.

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